

## THE TOTAL MASS OF THE EARLY-TYPE GALAXY NGC 4649 (M60)

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**SUMMARY:** In this paper we analyze the problem of the total mass and the total mass-to-light ratio of the early-type galaxy NGC 4649 (M60). We have used two independent techniques: the X-ray methodology which is based on the temperature of the X-ray halo of NGC 4649 and the tracer mass estimator (TME) which uses globular clusters (GCs) observed in this galaxy. We calculated the mass in Newtonian and MODified Newtonian Dynamics (MOND) approaches and found that interior to 3 effective radii ( $R_e$ ) there is no need for large amounts of dark matter. Beyond  $3R_e$  dark matter starts to play important dynamical role. We also discuss possible reasons for the discrepancy between the estimates of the total mass based on X-rays and TME in the outer regions of NGC 4649.

**Key words.** Gravitation – Galaxies: elliptical and lenticular, cD – Galaxies: kinematics and dynamics – Galaxies: individual: NGC 4649 – Cosmology: dark matter

## 1. INTRODUCTION

The problem of dark matter in early-type galaxies is still one of the most important unsolved (and, we might add, poorly understood) problems in the contemporary extragalactic astronomy and cosmology (e.g. Samurović 2007, Chap. 1, for a detailed introduction). For decades it was almost universally considered that the giant ellipticals are paramount reservoirs of dark matter, a prejudice partially based on the poor understanding of the Faber-Jackson relation linking the central velocity dispersion and the galactic luminosity. The general picture which seems to emerge with contemporary observational data, suggests that interior to  $\sim 2$ – $3$  effective radii,  $R_e$ , (inner regions) dark matter does not play any impor-

tant dynamical role (e.g. Samurović and Danziger 2005). At larger galactocentric distances (beyond  $\sim 3 - 4R_e$ ) it starts to play more important role; its contribution, however, varies from case to case (e.g. Samurović and Danziger 2006, Samurović 2006). Overall, there is still considerably smaller amount of observational data for elliptical than for spiral galaxies, which makes establishing general results very difficult.

In order to find a typical mass-to-light ratio characteristic for early-type galaxies, one can use the paper by van der Marel (1991) who found on a sample of 37 bright ellipticals that this quantity in the  $B$ -band is:  $M/L_B = (5.95 \pm 0.25)h_{50}$ ; thus  $M/L_B = 8.33 \pm 0.35$  for  $h = 0.70$  (the value of the Hubble constant used in this paper; see Tegmark et al. 2004). This sample pertained to inner parts

of ellipticals, and therefore we consider the absolute upper limit for the visible (stellar) component  $M/L_B \sim 9 - 10$ . Any inferred mass-to-light ratio above  $\sim 10$  in a given region would thus imply the existence of unseen (dark) matter there. Note that this conclusion is independent on whether the inner regions studied by van der Marel (1991) also contain significant amounts of dark matter (which is highly unlikely). We stress that the acceptance of large quantities of dark matter in the astrophysical community is not unanimous. One possible (and in some cases seemingly viable) alternative is MOND (MOdified Newtonian Dynamics), pioneered by Milgrom (1983), which will also be tested in the present paper.

Recently, new kinematical data of NGC 4649 which extend out to  $\sim 6R_e$ , based on the observations of globular clusters (GCs), became available (Lee et al. 2008). Samurović and Ćirković (2008, hereafter Paper I) used these data to study the velocity dispersion profile using the Jeans equation and found that the mass-to-light ratio  $M/L_B \sim 7$  provides a satisfactory fit of the velocity dispersion throughout the whole galaxy which implies the scarcity of dark matter in this galaxy. In the present paper our aim is to employ other independent techniques to calculate the total mass (and mass-to-light ratio) and compare the estimates obtained using different approaches (both Newtonian and MOND).

The plan of the paper is as follows: In Section 2 we present the basic observational data related to NGC 4649 which we use in this paper. In Section 3 we calculate the total mass of NGC 4649 in Newtonian mass-follows-light approach based on two different techniques: X-rays and tracer mass estimator (TME). In this section we also apply the virial theorem in order to calculate the total mass of this galaxy. In Section 4 we calculate the mass of NGC 4649 in MOND approach (using three different relationships) again based on the two aforementioned techniques, X-rays and TME. Finally, in Section 5 we discuss our findings and present the conclusions.

## 2. THE BASIC DATA

NGC 4649 (M60) is a giant elliptical galaxy in the Virgo cluster. It has a nearby companion, NGC 4647 (Sc galaxy at  $2.5'$  from the center of NGC 4649). The systemic velocity of NGC 4649 is  $v_{\text{hel}} = 1117 \pm 6 \text{ km s}^{-1}$ . Hereafter we use the distance based on this systemic velocity – for the recent WMAP estimate of the Hubble constant (Tegmark et al. 2004; Komatsu et al. 2008),  $h_0 = 0.70$  we obtain  $d = 15.96 \text{ Mpc}$ ; in this case 1 arcsec corresponds to  $77.5 \text{ pc}$ . For the effective radius, as in Paper I, we take  $R_e = 90 \text{ arcsec}$  (which is equal to  $6.97 \text{ kpc}$  for the distance which we use), the value taken from the paper by Kim et al. (2006). Note that there are different estimates in the literature, for example, Lee et al. (2008) took  $R_e = 110 \text{ arcsec}$  and according to the RC3 catalog (de Vaucouleurs et al. 1991),  $R_e = 69 \text{ arcsec}$ . Our adopted value is therefore an intermediate one. The discrepancy does not significantly impact our conclusions.

The kinematics of NGC 4649 which includes velocity dispersion and symmetric and asymmetric departures from the Gaussian is given in Fig. 1 of Paper I. The radial distribution of GCs is given in Fig. 2 of Paper I: it was shown that beyond  $\sim 1 \text{ arcmin}$  the surface number density can be fitted with a power law:  $\Sigma \propto r^{-\gamma}$ , where  $\gamma = 1.285$  and  $r$  is the distance to the galaxy center in projection.

As in Paper I we here use the observations of GCs from the study of Lee et al. (2008). This sample consists of 121 GCs (83 blue and 38 red GCs) and in all our calculations we always deal with the total sample in order to have a larger number of GCs per each bin.

## 3. TOTAL MASS IN NEWTONIAN GRAVITY

In this Section we present the total mass of NGC 4649 (and the total mass-to-light ratio in the  $B$ -band) in Newtonian gravity and in next Section we calculate the same quantities in MOND gravity.

To calculate Newtonian mass we use two different, independent techniques: X-rays and tracer mass estimator (TME). The estimates and comparison are given in Fig. 1 and in Table 1. In this Section we also use scalar virial theorem as a check for the estimate of the total mass of NGC 4649.

### 3.1 X-RAY ESTIMATE

The total mass of NGC 4649 interior to the radius  $r$  based on the X-ray observations is calculated using the following equation taken from Kim

and Fabbiano (1995):

$$M_T = 1.8 \times 10^{12} (3\beta + \alpha) \left( \frac{T}{1 \text{ keV}} \right) \left( \frac{r}{1000''} \right) \left( \frac{d}{10 \text{ Mpc}} \right) M_\odot, \quad (1)$$

where the exponent  $\alpha$  is related to the temperature of the X-ray halo ( $T \sim r^{-\alpha}$ ) and in our calculations taken to be zero, while  $\beta$  is the slope used in the analytic King approximation model and taken to be  $\beta = 0.50$  (Brown and Bregman 2001). The mass-to-light ratio in the  $B$ -band calculated as a function of radius  $r$  is given as:

$$\frac{M_T}{L_B} = 1.16 \times 10^{-2} 10^{\frac{B}{2.5}} (3\beta + \alpha) \left( \frac{T}{1 \text{ keV}} \right) \left( \frac{r}{1000''} \right) \left( \frac{d}{10 \text{ Mpc}} \right)^{-1}, \quad (2)$$

where  $B$  is the  $B$  magnitude of the galaxy inside radius  $r$  (Kim and Fabbiano 1995). In our estimates for the temperature in Fig. 1 we have used the results of Randall et al. (2006):  $T = 0.80 \pm 0.05 \text{ keV}$ .

It is important to note that the two relations above assume the existence of hydrostatic equilibrium, which is almost universal in interpreting the X-ray profiles. Based on the recent work of Diehl and Statler (2007) the optical and X-ray isophotes for NGC 4649 are very close: for X-rays (based on the CHANDRA observations) ellipticity  $\epsilon_X = 0.08 \pm 0.03$  and position angle  $\text{P.A.}_X = 95 \pm 27$  whereas in the optical domain  $\epsilon_{\text{opt}} = 0.18 \pm 0.01$  and  $\text{P.A.}_{\text{opt}} = 104.0 \pm 0.4$ . We interpret this as an indication of hydrostatic equilibrium; for NGC 1399 the discrepancy between these two quantities in X-ray and optical domain is much larger:  $\epsilon_X = 0.34 \pm 0.04$ ,  $\epsilon_{\text{opt}} = 0.10 \pm 0.1$ ,  $\text{P.A.}_X = 179 \pm 7$  and  $\text{P.A.}_{\text{opt}} = 107.4 \pm 0.1$ . The estimate of the total mass of NGC 1399 based on the X-rays is given in Samurović and Danziger (2006).

### 3.2 TRACER MASS ESTIMATOR

Evans et al. (2003) introduced a "tracer mass estimator" method which provides an estimate of the enclosed mass based on the projected positions and line-of-sight velocities of a given tracer population

(such as GCs in our case). We assume that the tracer population is spherically symmetric and has a number density that obeys a power law:

$$\rho(r) = \rho_0 \left( \frac{a}{r} \right)^{\gamma_1}, \quad (3)$$

where  $a$  is constant, and radius  $r$  ranges between  $r_{\text{in}}$  and  $r_{\text{out}}$ , inner and outer points of the given population, respectively. The parameter  $\gamma_1 = 2.285$  (we label this parameter  $\gamma_1$  to avoid confusion with the exponent found in Fig. 2 of Paper I) was determined using the surface density of the tracer population between  $r_{\text{in}}$  and  $r_{\text{out}}$ . Evans et al. give the following formula for the mass (supported by random motion) enclosed within  $r_{\text{in}}$  and  $r_{\text{out}}$  for the isotropic ("iso" in formulae below) case ("los" stands for line-of-sight):

$$M_p = \frac{C_{\text{iso}}}{GN} \sum_i v_{\text{los}i}^2 R_i, \quad (4)$$

where  $R_i$  is the projected position of the  $i$ -th object relative to the center of the galaxy,  $N$  is the size of the tracer population and the constant  $C_{\text{iso}}$  is given as:

$$C_{\text{iso}} = \frac{4}{\pi} \frac{\gamma_1}{3 - \gamma_1} \frac{4 - \alpha - \gamma_1}{1 - (r_{\text{in}}/r_{\text{out}})^{3 - \gamma_1}}. \quad (5)$$

This expression is for the case of an isothermal potential (gravity field is assumed to be scale-free,  $\psi = -v_0^2 \log r$ , see Evans et al. 2003 for details); we have also used the isotropic case (for visible matter; for dark matter nothing is assumed) for the sake of simplicity, given the small departures from zero of the parameter  $s_4$  which describes asymmetric departures from the Gaussian (see Paper I).

To obtain the total mass of the galaxy we must also take into account the rotational component which is equal to:

$$M_{\text{rot}} = \frac{v_{\text{rot}}^2 R_{\text{out}}}{G}, \quad (6)$$

where  $R_{\text{out}}$  is the outermost tracer projected radius in the sample. Therefore, the total mass of NGC 4649 is equal to the sum:

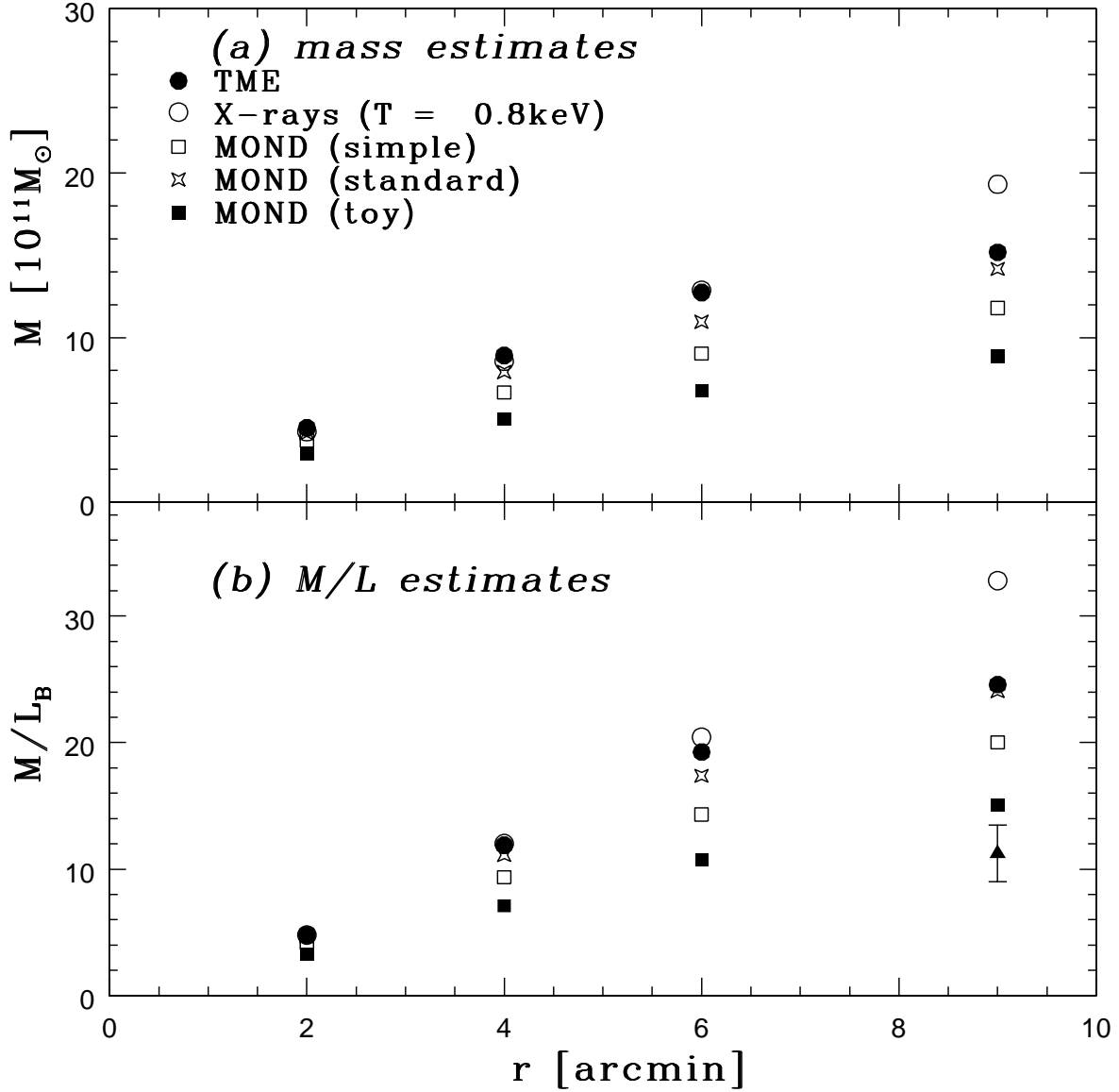
$$M_{\text{tot}} = M_p + M_{\text{rot}}. \quad (7)$$

**Table 1.** Newtonian and MOND mass and M/L estimates for NGC 4649*The table was split in two parts in this preprint.*

r	$M_{\text{tot}}^{\text{xray}}$	$M^{\text{xray}}/L_B$	$M_{\text{tot}}^{\text{TME}}$	$M^{\text{TME}}/L_B$	$M_{\text{tot}}^{\text{M,sim}}$	$M^{\text{M,sim}}/L_B$
(')	$10^{11} M_{\odot}$	$M_{\odot}/L_{\odot}$	$10^{11} M_{\odot}$	$M_{\odot}/L_{\odot}$	$10^{11} M_{\odot}$	$M_{\odot}/L_{\odot}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
<2	$4.3 \pm 0.6$	$4.8 \pm 0.7$	$4.5 \pm 0.4$	$4.8 \pm 0.4$	$3.8 \pm 0.5$	$4.2 \pm 0.6$
<4	$8.6 \pm 1.2$	$12.0 \pm 1.7$	$8.9 \pm 1.2$	$11.9 \pm 1.6$	$6.7 \pm 0.9$	$9.4 \pm 1.3$
<6	$12.9 \pm 1.8$	$20.4 \pm 2.9$	$12.8 \pm 2.1$	$19.3 \pm 3.2$	$9.0 \pm 1.3$	$14.3 \pm 2.0$
<9	$19.3 \pm 2.8$	$32.8 \pm 4.6$	$15.2 \pm 3.0$	$24.6 \pm 4.9$	$11.8 \pm 1.7$	$20.0 \pm 2.8$

r	$M_{\text{tot}}^{\text{M,std}}$	$M^{\text{M,std}}/L_B$	$M_{\text{tot}}^{\text{M,toy}}$	$M^{\text{M,toy}}/L_B$
(')	$10^{11} M_{\odot}$	$M_{\odot}/L_{\odot}$	$10^{11} M_{\odot}$	$M_{\odot}/L_{\odot}$
(1)	(8)	(9)	(10)	(11)
<2	$4.2 \pm 0.6$	$4.7 \pm 0.7$	$2.9 \pm 0.4$	$3.3 \pm 0.5$
<4	$7.9 \pm 1.1$	$11.1 \pm 1.6$	$5.1 \pm 0.7$	$7.1 \pm 1.0$
<6	$11.0 \pm 1.5$	$17.4 \pm 2.4$	$6.8 \pm 1.0$	$10.8 \pm 1.5$
<9	$14.2 \pm 2.0$	$24.1 \pm 3.4$	$8.9 \pm 1.3$	$15.0 \pm 2.1$

NOTES – Col. (1): radius interior to which a given quantity is calculated, expressed in arc minutes. Col. (2): estimate of the cumulative mass based on the X-ray methodology, expressed in units of  $10^{11} M_{\odot}$  for  $T = 0.80 \pm 0.05$  keV. Col. (3): mass-to-light ratio based on the X-ray methodology, in the  $B$ -band, in solar units for  $T = 0.80 \pm 0.05$  keV. Col. (4): estimate of the cumulative mass based on the TME methodology, expressed in units of  $10^{11} M_{\odot}$  for the isotropic case. Col. (5): mass-to-light ratio based on the TME methodology, in the  $B$ -band, in solar units. Col. (6): estimate of the cumulative mass based on the MOND "simple" model (see text for details). Col. (7): mass-to-light ratio based on the MOND "simple" model, in the  $B$ -band, in solar units. Col. (8): estimate of the cumulative mass based on the MOND "standard" model (see text for details). Col. (9): mass-to-light ratio based on the MOND "standard" model, in the  $B$ -band, in solar units. Col. (10): estimate of the cumulative mass based on the MOND "toy" model (see text for details). Col. (11): mass-to-light ratio based on the MOND "toy" model, in the  $B$ -band, in solar units. The distance  $d = 15.96$  Mpc was always used.



**Fig. 1.** Total Newtonian and MOND mass (upper panel) and Newtonian and MOND mass-to-light ratio (lower panel). In the Newtonian approach we used "tracer mass estimates" and X-ray halo with temperature  $T = 0.80$  keV according to the observational data of Randall et al. (2006). In the MOND approach we tested three different models: "simple", "standard", and Bekenstein's "toy" model (see text for details). Additional point in the lower panel at 9 arcmin given with the filled triangle corresponds to the MOND estimate of the total mass-to-light ratio based on the "toy" model and the TME methodology. The distance  $d = 15.96$  Mpc is used everywhere.

From Fig. 1 it can be seen that the estimates based on two physically very different methodologies are very similar (especially interior to  $\sim 6$  arcmin), thus providing the strong evidence for the increase of mass (and the mass-to-light ratio) in NGC 4649 in Newtonian gravity. The discrepancy between the

two methodologies and its consequences will be discussed below.

### 3.3 VIRIAL ESTIMATE

In order to establish the total mass of NGC 4649, we can also use scalar virial theorem for a stationary stellar system (Bertin et al. 2002):

$$\frac{G\Upsilon_*L}{R_e} = K_V\sigma_0^2, \quad (8)$$

where  $\Upsilon_*$  is the *stellar* mass-to-light ratio in the given band,  $L$  is the luminosity of the galaxy and  $\sigma_0$  is the central velocity dispersion referred to an aperture radius of  $R_e/8$ .  $K_V$  is the so-called "virial coefficient" which takes into account the projection effects. Cappellari et al. (2006) showed that  $K_V = 5 \pm 0.1$  for a sample of early-type galaxies at redshift  $z \sim 0$ . From this equation the total dynamical mass is:

$$M_{\text{dyn}} = K_V \frac{\sigma_0^2 R_e}{G}. \quad (9)$$

Using the aforementioned value for  $K_V = 5$ ,  $\sigma_0 = 230 \text{ km s}^{-1}$ , and  $R_e = 6.97 \text{ kpc}$ , one obtains the total dynamical mass of NGC 4649:  $M_{\text{dyn}} = (4.2 \pm 1.3) \times 10^{11} M_\odot$ . This value takes into account only *random* motions and it does not take into account the rotational support so it is necessarily lower than the true value. Taking into account Eq. (6), we get at  $3R_e$   $M_{\text{rot}}(3R_e) = (0.9 \pm 0.7) \times 10^{11} M_\odot$  (for  $v_{\text{rot}} = 141 \text{ km s}^{-1}$ ). Thus, the total dynamical mass within  $3R_e$  ( $= 3'.45$ ) is equal to  $(5.1 \pm 2.0) \times 10^{11} M_\odot$  which is very close to the values obtained using X-ray and TME methodologies at the same galactocentric distance (see Table 1). We note that in our estimate of the dynamical mass we have used the value of  $\sigma_0$  inferred from the kinematics of the GCs. If we use the value of the velocity dispersion based on the integrated stellar spectra (Fisher et al. 1995),  $\sigma_0 = 325 \text{ km s}^{-1}$  a higher value of the total dynamical mass (rotational support is assumed) is obtained:  $M_{\text{dyn}} = (9.3 \pm 2.0) \times 10^{11} M_\odot$ . This is even closer to the values based on the TME and X-ray methodologies (see Table 1).

The role of the rotation in early-type galaxies was discussed recently by van der Wel et al. (2008) who studied the sample of these galaxies between redshift  $z = 1$  and the present epoch  $z \sim 0$  and found that for rotating galaxies  $K_V$  is possibly  $\sim 20\%$  larger than the canonical value of 5. They used Eq. (9) only, in order to establish the total mass of the galaxies in their sample. We see that in the case of NGC 4649, the contribution of the rotation, equal to  $M_{\text{rot}}/M_{\text{dyn}} = 0.9 \times 10^{11} M_\odot / 4.2 \times 10^{11} M_\odot \approx 0.21$ , is close to that given by van der Wel et al., i.e. the mass is  $\sim 21\%$  larger when we take the rotation into account, as given above.

### 4. TOTAL MASS IN MOND GRAVITY

In this Section we calculate the total mass of NGC 4649 in MOND gravity using three different formulas: (i) the "simple" MOND formula from Famaey and Binney (2005), (ii) the "standard" formula (Sanders and McGaugh 2002) and (iii) the Bekenstein's "toy" model (Bekenstein 2004). The Newtonian acceleration is written as  $a_N = a\mu(a/a_0)$  where  $a$  is the MOND acceleration and  $\mu(x)$  is the MOND interpolating function where

$$x \equiv \frac{a}{a_0}. \quad (10)$$

Here,  $a_0 = 1.35_{-0.42}^{+0.28} \times 10^{-10} \text{ m s}^{-2}$  is a new universal constant required by MOND (Famaey et al. 2007). The interpolation function  $\mu(a/a_0)$  shows the asymptotic behavior,  $\mu \approx 1$ , for  $a \gg a_0$ , so that one obtains the Newtonian relation in the strong field regime, and  $\mu = a/a_0$  for  $a \ll a_0$ .

As we have shown in Paper I the "external field effect" does not play an important role in the case of NGC 4649 so we will neglect it in our calculations below.

The MOND dynamical mass,  $M_M$  can be expressed by using the Newtonian one within a given radius  $r$ ,  $M_N$ , through the following expression (e.g. Angus et al. 2008):

$$M_M(r) = M_N(r) \times \mu(x). \quad (11)$$

The interpolation function can have different forms as given below (we refer the reader to Paper I regarding our MOND calculations and the details related to the variable  $x$  and the expressions for the circular velocity  $v_{\text{circ}}$  in MOND approach). We note that the Newtonian mass,  $M_N$  is always based on Eq. (1) unless stated otherwise.

A "simple" MOND formula is given as:

$$\mu(x) = \frac{x}{1+x}. \quad (12)$$

A "standard" MOND formula is given as:

$$\mu(x) = \frac{x}{\sqrt{1+x^2}}. \quad (13)$$

Finally, for the "toy" model of Bekenstein the MOND formula is:

$$\mu(x) = \frac{-1 + \sqrt{1+4x}}{1 + \sqrt{1+4x}}. \quad (14)$$

The results for the total mass and mass-to-light ratio are given in Fig. 1 and Table 1. The uncertainties due to the error for the temperature and

the errors for the  $a_0$  parameter are also given in Table 1. All predictions imply the existence of dark matter beyond  $\sim 3R_e$ , with the exception of the Bekenstein "toy" model based on the TME methodology, which is marginally consistent with no dark matter hypothesis (see Fig. 1).

## 5. DISCUSSION AND CONCLUSIONS

We used the kinematics of 121 GCs and the X-ray observations of the early-type galaxy NGC 4649 in order to examine its mass profile. We performed our calculations in Newtonian and MOND approaches with the goal of establishing the existence (or lack) of dark matter in this galaxy. In Paper I we found that the velocity dispersion of this galaxy can be fitted with  $M/L_B \sim 7$  implying a low amount of dark matter, if any. Judging from the approximately constant value of the velocity dispersion in the bins at various galactrocentric distance from the center we found a hint of increasing mass-to-light ratio in the outer bins, i.e. we could not exclude the mass-to-light ratio as high as 15 in the outermost bin (beyond  $\sim 8$  arcmin) (see Fig. 3 of Paper I).

Our results are as follows:

1) Interior to  $\sim 3R_e$  ( $=270$  arcsec) we find no support for the significant amounts of dark matter. Both TME and X-ray methodologies predict the mass-to-light ratio  $M/L_B \sim 12$  (in the Newtonian approach) which is higher than the value obtained using the Jeans modelling (see Paper I) but given the error bars (see Table 1) we see that the amount of dark matter may indeed be very low. In the MOND approach the predicted mass-to-light ratio is lower (between  $\sim 7$  and  $\sim 9$ ) which is obviously consistent with the absence of dark matter interior to this radius. The virial estimate of the total dynamical mass based on the velocity dispersion inferred from the kinematics of the GCs ( $\sigma_0 = 230 \text{ km s}^{-1}$ ) is lower than the estimate which we obtain using the velocity dispersion based on the integrated stellar spectra ( $\sigma_0 = 325 \text{ km s}^{-1}$ ); the latter value is in a very good agreement with the estimates obtained using both X-ray and TME methodologies.

2) Beyond  $\sim 3R_e$  the situation becomes more complex: both X-ray and TME methodologies predict rapid increase of the total mass (and the mass-to-light ratio) implying the existence of the dark component which starts to dominate. Both methodologies provide a very similar prediction: interior to 6 arcmin ( $4R_e$ ) the mass-to-light ratio becomes  $M/L_B \sim 20$  which implies at least 50% of the dark matter contribution. At 9 arcmin ( $6R_e$ ) the predictions of the two methodologies differ: the X-rays estimate ( $M/L_B \sim 33$ ) is much higher than that based on TME, ( $M/L_B \sim 25$ ): note that the estimates are nevertheless consistent given the larger error bars in the last bin. The predictions of both method-

ologies imply significant amounts of dark matter in the outer regions of NGC 4649 in the Newtonian approach. MOND estimates are lower but for the estimates based on the X-rays one still needs significant amounts of dark matter in the outer regions. There is only one case for which we managed to have rather low mass-to-light ratio in the MOND approach: this is a case based on the TME methodology and the Bekenstein's "toy" formula. At 9 arcmin  $M/L_B = 11.3 \pm 2.2$  which is marginally consistent with the absence of dark matter (see Fig. 1). While this marginal consistency may present the "last resort" for the MOND proponents, one should also point out that all other encouraging results of the MOND approach have been obtained using different models (which we have dubbed "simple" and "standard"), which in this case require large quantities of dark matter, thus obviating the motivation for such a radical approach as MOND in the first place.

3) The question of the discrepancy between the X-ray and TME mass estimates remains open. One of the possible reasons could be the deviation from hydrostatic equilibrium in NGC 4649. We do not consider this as a crucial issue in the present case (see the discussion at the end of Section 3.1). One possible reason can be the lower gas temperature in the outer regions of NGC 4649. This could be related to the reheating in the central regions, along the lines set by the model of evolving cooling flows by Binney and Tabor (1995). Note that the last measured point in the study of Randal et al. (2006, table 4) is interior to  $\sim 200$  arcsec which is well inside  $3R_e$ , i.e. within the region where all approaches agree on the predicted total mass. In order to resolve this question it is necessary to have the X-ray observations which extend beyond  $\sim 3R_e$  and to have more observed GCs in the outer bins so as to reduce the uncertainties related to the kinematical profile of NGC 4649.

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